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Direct fabrication of joints based on direct metal laser sintering in aluminum and titanium alloys

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Abstract

Application of direct metal laser sintering for manufacturing three-dimensional objects represents one of the promising directions for the industries. Through this technology is possible to create an object with desired shape and material properties in order to meet a variety of applications. However, most reported applications are for static parts. There are only limited reports about direct rapid fabrication of mechanisms that could be considered as the core subsystems for many machine and robotic designs. So the main purposes of this study are the investigation and application of direct metal laser sintering (DMLS) in fabricating non-assembly mechanisms systems in AlSi10Mg and Ti6Al4V alloys.

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Keywords: direct metal laser sintering; mechanism; joints; aluminum alloy; titanium alloy

1. Introduction

The advantages of using additive manufacturing (AM) techniques in mechanism and robot design and fabrication are numerous. Physical prototypes of the mechanism can be obtained in a short time and improve the quality of the design process thanks to the possibility to evaluate the uncertain configurations. By using these physical prototypes, several properties of the mechanisms can be evaluated immediately such as: determination of the internal mobility of link interference, and visualization of joint limits. Moreover, AM allows one step fabrication of complex three-dimensional structures and of multi-articulated system, which could not be produced with conventional fabrication processes, without requiring assembly of its structural members and joints after fabrication. One step fabrication technique can drastically change the way that mechanisms are currently built. However, only limited studies have investigated the direct fabrication of non-assembly mechanisms using AM. Rajagopalan and Cutkosky [1] formulated a general technique for investigating the kinematic performance on mechanisms fabricated as non-assembly using layer-based machines. The technique admits only deterministic and stochastic error estimation for mechanisms with ideal joints. Errors due to joint clearances, and form errors which are prominent for AM-based mechanism fabrication were not considered. Mavroidis et al. [2] built several types of joint such as revolute joint, spherical joint, prismatic joint and universal joint. Lipson et al. [3] reproduced several historic mechanisms in acrylonitrile-butadiene-styrene (ABS) and their main purpose was just to duplicate the mechanisms without further analysis of the mechanism accuracy. Park et al. [4] used AM technologies for fabrication of a humanoid biped robot predominantly assembled by revolute joints. These studies are about fabrication of mechanisms in polymeric materials using 3D printing, stereolithography (SLA) and selective laser sintering (SLS) machines. AM-fabricated metallic mechanisms can have many potential practical applications, since they have high strength, which can stand loads in many operations. Selective laser melting (SLM) is the most challenging technology among a broad range of AM processes for the fabrication of metallic parts. However, the joint clearances of

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mechanisms are always very small and during SLM manufacturing, the trapped powdered material and the added supports within clearance may lead to a failing fabrication. Chen et al. [15] proposed a drum-shaped pin joint design to simplify the removal of trapped material, but the pin shape would be complicated when it connects several links. Therefore, they developed another improved joint design. In this paper they also discussed the display and fabrication of mechanisms are discussed to further reduce the support count, since metallic support structures are often not so easily removed as polymer ones. Su et al. [6] redesigned a joint to facilitate powdered material removal and the corresponding support additions within the clearances were analyzed. A series of universal joint were directly fabricated using SLM machine with a minimum clearance of 0.1mm. It was observed that the mobility of the joints is largely dependent on the clearance assigned. A small clearance may not allow any motion in the joint, yet a large clearance will cause joint vibration and instability.

This paper presents a study on possible ways to reduce the joint clearance while keeping the mobility of joints in mechanisms and multi-articulated structures (like robotic systems) manufactured in one step called non-assembly mechanisms, in aluminum and titanium alloys.

2. Joint design

As mentioned above, the determination of clearances is fundamental in the successful fabrication of mechanisms, especially in non-assembly fabrication. In previous research studies [5-7] a drum shaped pin joint design to maintain joint mobility with a small clearance in which are inserted the supports was proposed. In particular, as shown in Fig. 1 [7], the main idea was to necessarily involve the use of support structures in order to avoid distortions.

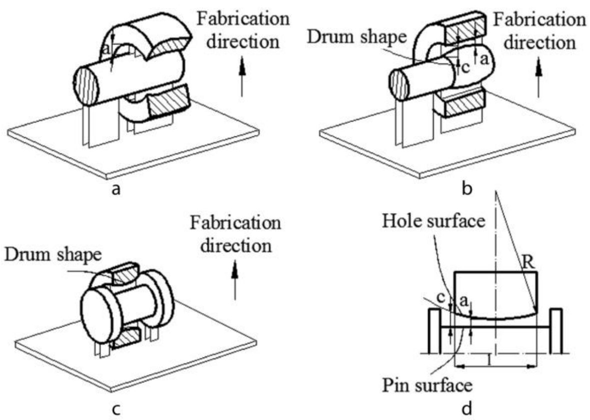

Fig. 1. (a) Conventional pin joint; (b) drum-shaped pin joint; (c) drum-shaped hole joint; (d) schematic of the geometric relationship [7]

However, it should be considered that the supports influence not only the surface quality but also the joint mobility. The problem is that it is difficult to remove the supports within the very small clearance. Moreover, in the field of the AM it is well known that a hole to maintain its circularity must be built with its main axis parallel to the fabrication direction. But this is not always possible due to the geometry of the parts. On the other hand, the assembly angle of mechanism can be adjusted for more orientations by moving the parts along the unconstrained degree of freedom, which make it possible to approach a configuration with fewer supports within the clearance. To find the best orientation, it is necessary to know the threshold values for the building of certain geometries, such as the overhang, the thin walls and small features, in order to prevent the warping and/or collapsing of the part. In any building orientation, the part is defined with its base on the xy-plane, the building direction along the z axis and the angle θ defined as the angle between the normal vector to the face (n) and vector normal of a slicing direction. When the intersection angle θ is equal to or less than the critical value, the region needs adding support (Fig. 2).

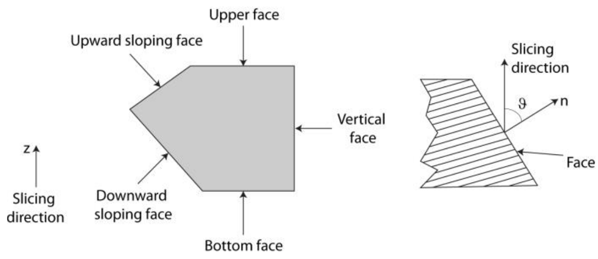

Fig. 2. Types of surfaces

In a previous study [8], it was demonstrated that it is possible to build parts without supports at angles up to 30° but they have a higher surface roughness probably due to the staircase effect. The stair size decreases proportionally with the cosine of the sloping angle. As the angle decreases, the staircase effect increases, meaning that the size of each step increases. When the minimum orientation is 45°, the maximum overhanging step (layer) size was the same size as the layer thickness (30μm). It is apparent that this is the maximum layer overhang, because greater than 30μm caused residual curl distortion during the SLM build. Based on this information, the joints can be redesigned as self-supporting structures. Fig. 3 shows the two pin joints proposed in this study.

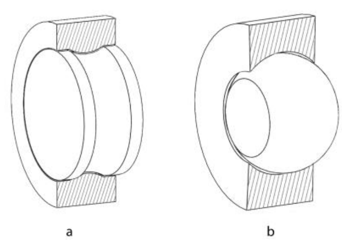

Fig. 3. a) Concave shaped pin and convex shaped hole joint; b) convex shaped pin and concave shaped hole joint

For each joint, both the hole and pin, presented a curvature in order to eliminate the problem of the distortions in the bottom face. The curvature is calculated by assuming that a structure elliptical in shape presents more smooth stress distribution with respect to one cylindrical in shape [9].

3. Fabrication experiment

The aluminum and titanium test joints were prepared by direct metal laser sintering (EOS Gmbh tradename for SLM) with an EOSINT M270 Xtended version. In this machine, a powerful Yb (Ytterbium) fiber laser system in an Ar atmosphere is used to melt powders with a continuous power up to 200 W. The detail of the DMLS process, together with the choice of the process parameters (Table 1) to obtain a part with the highest density and the best surface finishing, were described in an earlier study for the aluminum alloy [10]. Default machine process parameters were used for the titanium alloy (Table 1). As scanning strategy, the direction of scanning is rotated of 67° between consecutive layers [11].

Table 1. DMLS process parameters for aluminum alloy, optimized ones [10], and for titanium alloy, standard ones.

Parameters	*AlSi10Mg*		
	Skin	Core	Contour
Scan speed [mm/s]	900	800	900
Laser power [W]	120	195	80
Hatching distance [mm]	0.10	0.17	-
Layer thickness [µm]	30	30	-
Laser spot size [mm]	0.10	0.10	0.10
	Ti6Al4V		
Scan speed [mm/s]	1000	1250	1250
Laser power [W]	150	170	120
Hatching distance[mm]	0.10	0.10	-
Layer thickness [µm]	30	30	-
Laser spot size [mm]	0.10	0.10	0.10

For feasible verification of the direct fabrication of mechanism, the two configurations of the previously described joints were used to design and produce two non-assembly mechanisms: a convex shaped pin and concave shaped hole joint to be fabricated in titanium alloy (Fig. 4a), and a simple gear train mechanism with concave shaped pin and convex shaped hole joint (Fig. 4d), to be fabricated in aluminum alloy. Different values of clearance were considered: from 0.12 to 0.08 mm, decreasing with a step of 0.02 mm. The joints were fabricated with the orientation on the building platform and with the supports illustrated in Fig. 4c and 4f. When selecting the fabrication direction, the clearances should be displayed in a configuration without supports. These were inserted only externally in order to avoid the collapse of the parts, as illustrated previously in Fig. 4c and 4f. The support structures were also optimized to facilitate their disposal in detaching the parts from the building platform.

The non-assembly mechanisms were shot-peened after being removed from the platform. The shot-peening process was performed with glass microspheres using a sandblasting machine, SD9 Northblast, in order to improve their surface finishing, as already demonstrated in a previous study [10].

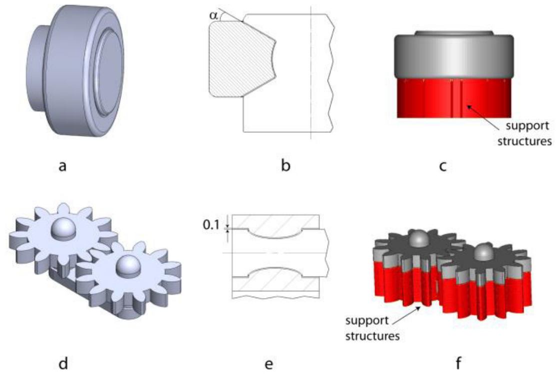

Fig. 4. a) Convex shaped pin and concave shaped hole joint; b-e) profile of the job; c-f) orientation in the building platform and support structures; d) simple gear trains mechanism with concave shaped pin and convex shaped hole joint

4. Results and discussion

The mobility and the stability of the joint are largely dependent on the clearance assigned and this derives by many features, such as the design of the joint, the orientation on the building platform and the powder material. It is well known that aluminum alloy powders differ a lot with respect to titanium alloy powders in terms of flowability on the building platform and reflectivity to the laser source. And the same part built by DMLS in titanium alloy present a surface roughness lower than those in aluminum alloy (mean surface roughness values are $R_{a,\ titanium}$ = 5 µm and $R_{a,\ aluminum}$ = 15 µm). Another important aspect to bear in mind is the different shrinkage related to the two type of metal alloys considered. Therefore, it is difficult to assign a certain minimum clearance. Moreover for the gear train mechanism, considering the clearances between the gears, and between the gear axle and the stationary part of the model, an empty space must be taken into account to ensure the correct movement of the rotating parts.

It was observed that it is possible to fabricate the two types of joints previously described, both in aluminum and titanium alloys, as shown in Fig. 5.

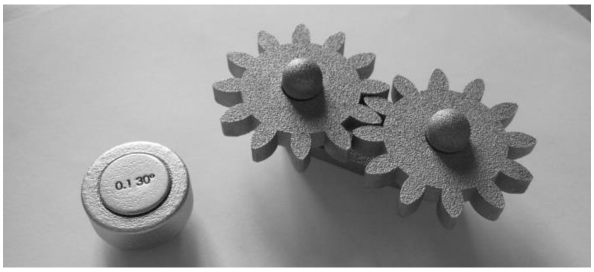

Fig. 5. Example of joints manufactured by DMLS with clearance of 0.1 mm (simple joint in titanium alloy) and 0.08 mm (gear trains in aluminum alloy).

In this study, the clearances were assigned decreasing until the chosen joint could not move smoothly. The above verification has shown that with a clearance of 0.12 mm the two types of joints could move but they were a little bit unstable, in both aluminum and titanium. Also with a value of 0.1 mm the joints could move smoothly. Differences arose with the minimum value 0.08 mm of clearance. As expected, the parts built in titanium had a greater definition that allowed a more fluid motion in the joint in comparison to the aluminum parts. In fact they showed clearly an increased friction. In this case there was the need to impart initially a greater force in order to give the rotational movement to the joint. Moreover, the aluminum joints had a higher deterioration than titanium ones. It could be concluded that for this type of aluminum alloy, the clearance tends to increase during use and thus makes the joint unstable.

The construction of the two joints showed that it is feasible to produce mechanisms non-assembled under a reasonable fabrication strategy. However, the creation of non-assembled mechanism means that the parts cannot be disassembled to improve the surface quality and thus the relative sliding friction between the contact surfaces during kinematic motion. A tilted orientation of the part respect to the axis of construction is always to be preferred recalling that over some threshold values the surface roughness increases due to the staircase effect. Therefore, in order to make this technology competitive for the kinematic mechanisms, it could be assumed that there is the need of a specific post-process able to improve the quality of the joint inner surfaces, employing for example a flux of an abrasive-laden fluid.

5. Conclusion

In this paper the fabrication of non-assembly mechanisms by DMLS in aluminum and titanium alloys was investigated and demonstrated. The main factors that affect the construction are the design and orientation of the parts as well as the type of material used. One of the main limits of the additive technologies for metals is the surface finish, especially for some materials such as aluminum alloys. The high roughness could create frictions between the contact surfaces during the kinematic movement. So it could be stated that it becomes necessary to use a finishing post-process specifically for interior surfaces, holes, cavities, and other areas that may be difficult to reach with other polishing or grinding processes.

References

[1] Rajagopalan S, Cutkosky M. Error analysis for the in-situ fabrication of mechanisms. ASME J Mech Des 2001;125:809-22.
[2] Mavroidis C, DeLaurentis KJ, Won J. Fabrication of non-assembly mechanisms and robotic system using rapid prototyping. Transaction of the ASME 2001;123:516-524.
[3] Lipson H, Moon FC, Hai J. 3-D printing the history of mechanisms. J Mech Des 2005; 127:1029-1033.
[4] Park K, Kim YS, Kim CS. Integrated application of CAD/CAM/CAE and RP for rapid development of humanoid biped robot. J Mater Process Tech 2007; 187: 609-613.
[5] Chen YH, Chen ZZ. Joint analysis in rapid fabrication of non-assembly mechanisms. Rapid Prototyping J 2011; 17:408-417
[6] Su X, Yang Y, Wang D. Digital assembly and direct fabrication of mechanism based on selective laser melting. Rapid Prototyping J 2013; 19:166-172.
[7] Yang Y, Su X, Wang D, Chen Y. Rapid fabrication of metallic mechanism joints by selective laser melting. P I Mech Eng B-J Eng 2011; 225: 2249-2256.
[8] Calignano F, Manfredi D. Production of overhanging structures by DMLS. In: Bartolo et al., editors. High Value Manufacturing. London: Taylor & Francis Group; 2014. p.61–64.
[9] Horng TL. A numerical algorithm A numerical algorithm for determining the contact stress of circular crowned roller compressed between two flat plates. JSME 2007; 1: 58-68.
[10] Calignano F, Manfredi D, Ambrosio EP, Iuliano L, Fino P. Influence of process parameters on surface roughness of aluminum parts produced by DMLS. Int J Adv Manuf Tech 2013; 67:2743–275.1
[11] Manfredi D, Calignano F, Krishnan M, Canali R, Ambrosio EP, Atzeni E. From Powders to Dense Metal Parts: Characterization of a Commercial AlSiMg Alloy Processed through Direct Metal Laser Sintering. Materials 2013; 6:856-869.